The 2^{nd} Hyper-K detector in Korea

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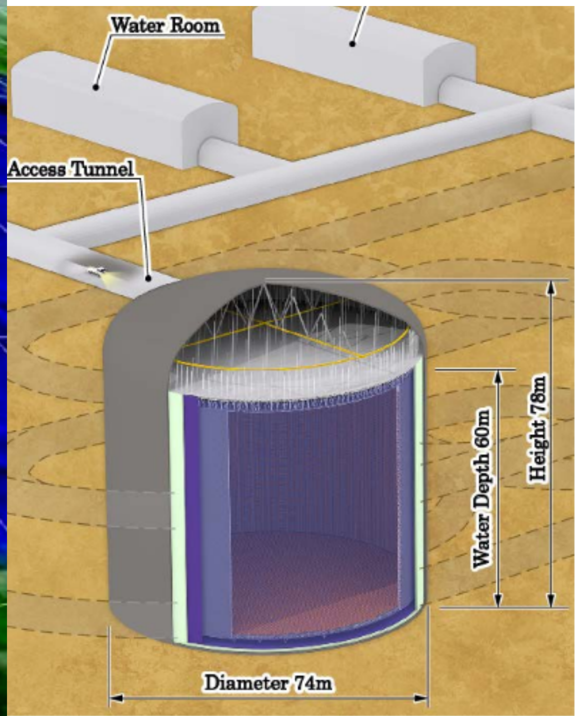
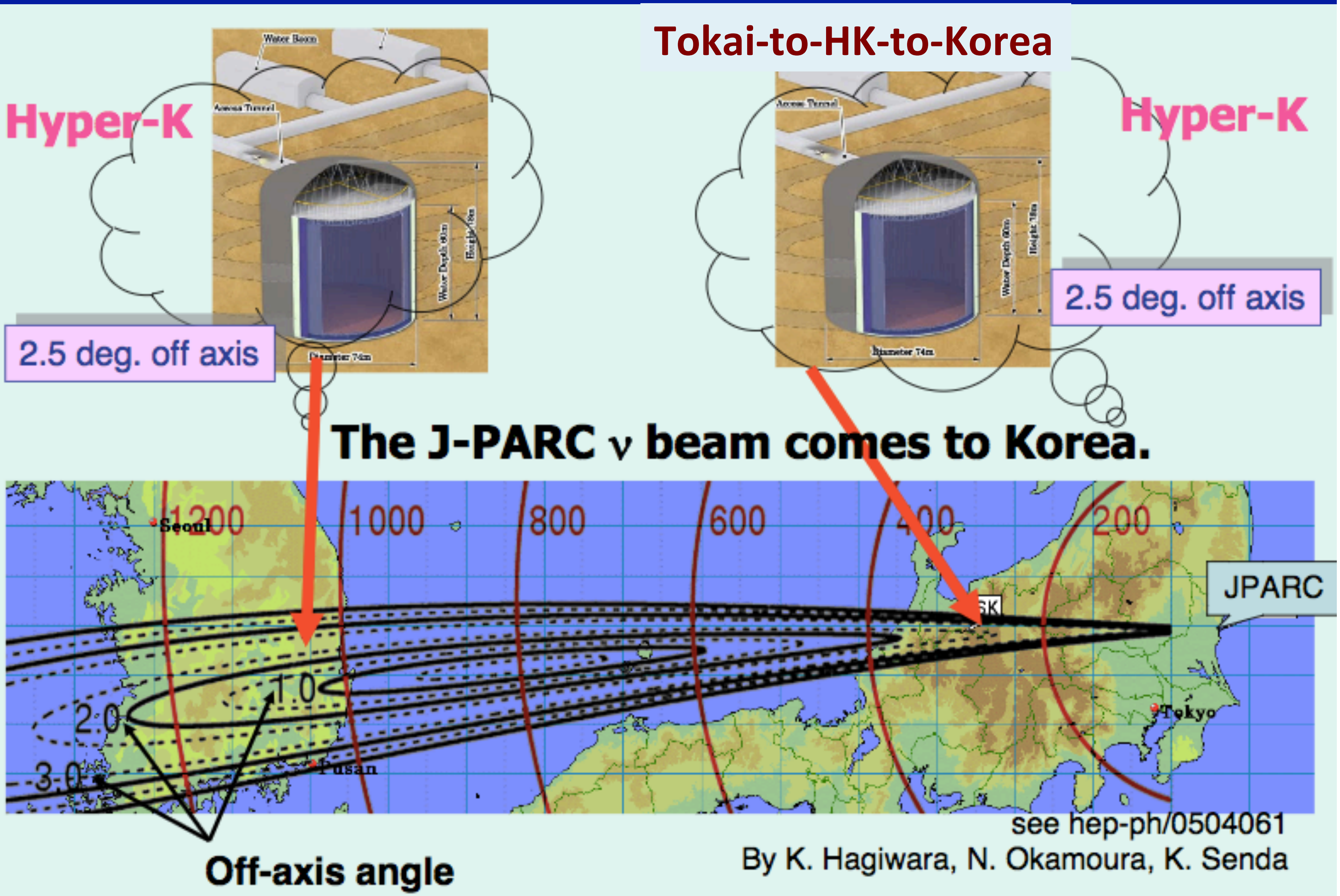


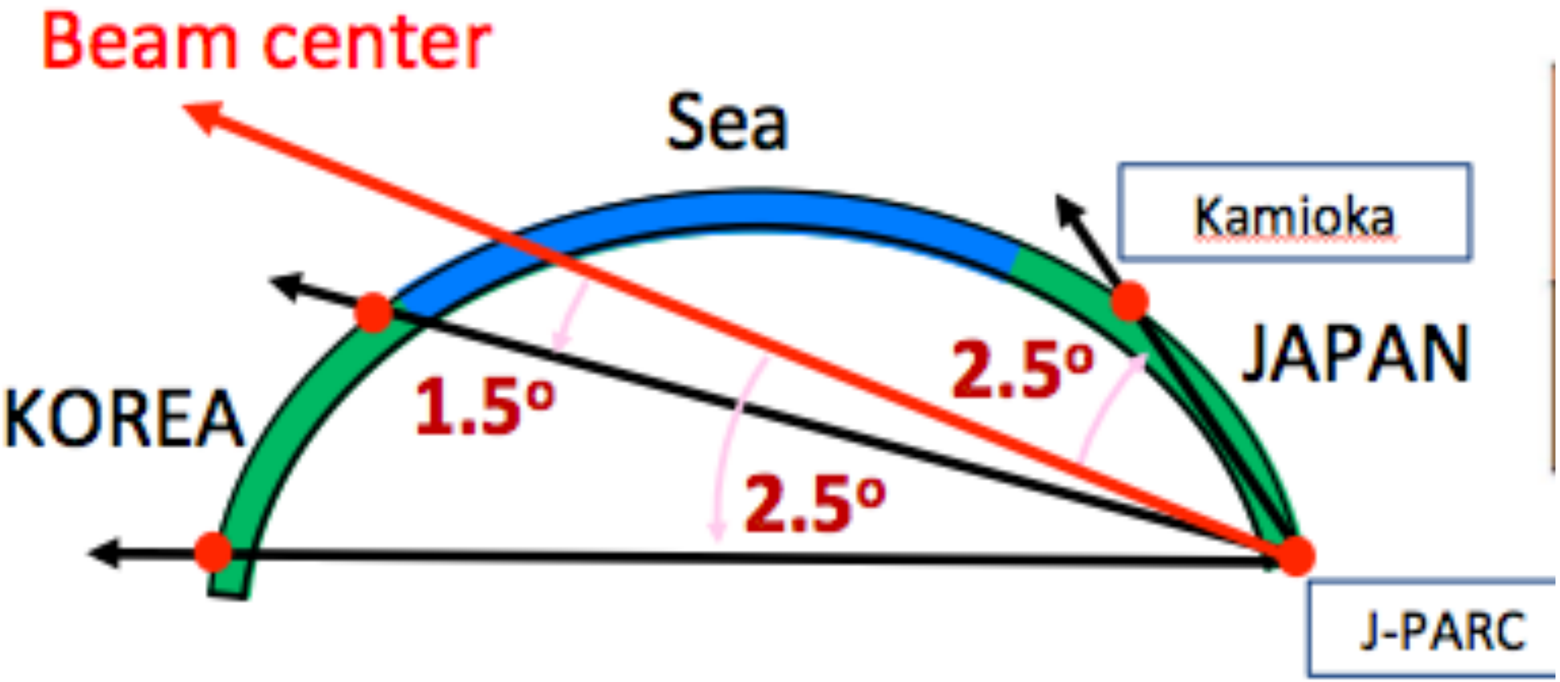
FroST
Oct. 24th 2016,
Mainz

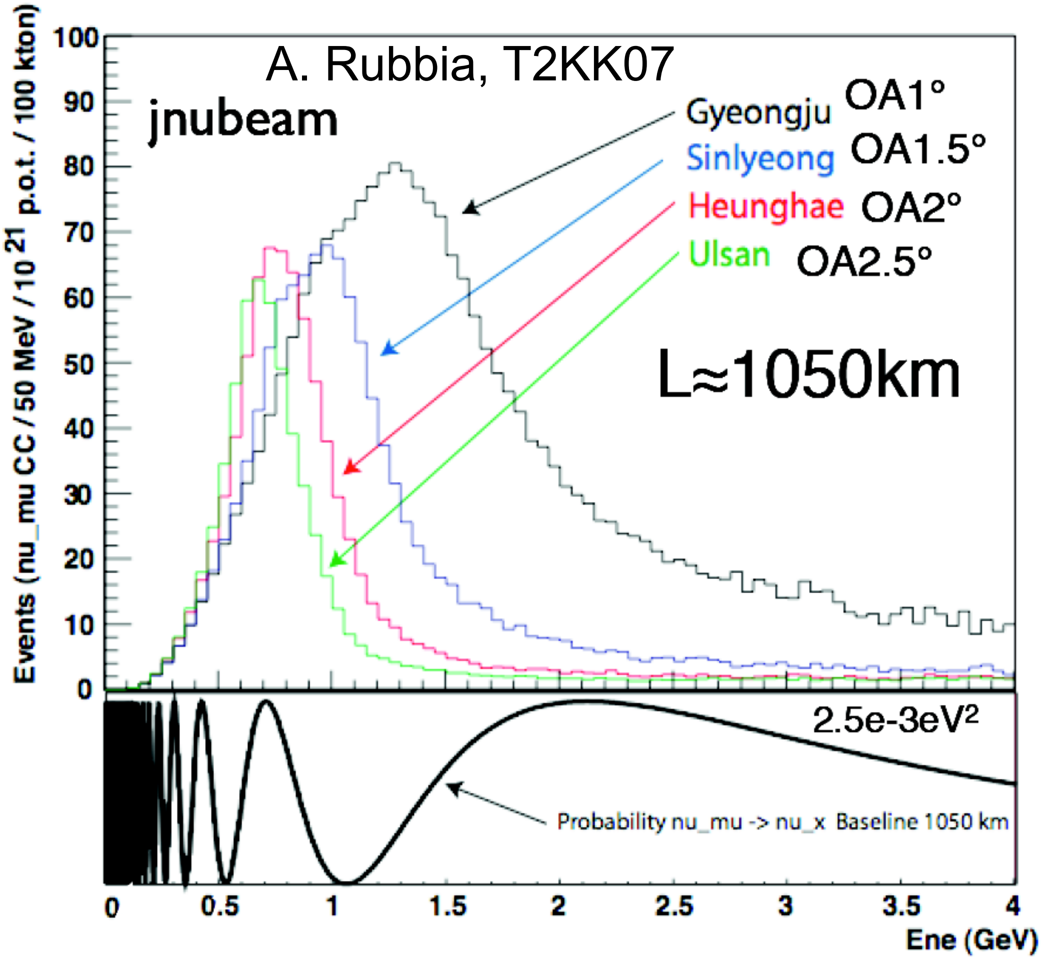
T2KK → T2HKK



Tokai-to-HK-to-Korea
Hyper-K
2.5 deg. off axis
Hyper-K
2.5 deg. off axis
The J-PARC ν beam comes to Korea.
Seoul
1200
1000
800
600
400
200
SK
JPARC
1.0
2.0
3.0
Pusan
Tokyo
Off-axis angle
see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Off-axis Beam



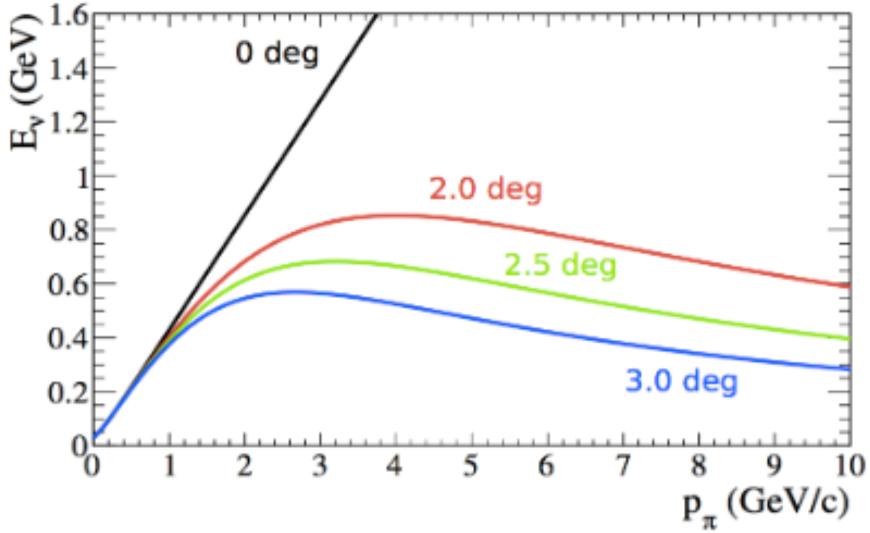


Pion mass

$$E_\nu = \frac{M^2 - m_\mu^2}{2(E - p\cos\theta)}$$

Pion energy

Pion momentum



T2HKK Physics Reach

Physics programs: the same as the Hyper-K
Physics sensitivities: better in the following topics

- **CP violation phase measurement**
- **Neutrino mass ordering determination**
- Non-standard neutrino interaction

} Beam Neutrinos (T2HKK)

- Solar neutrinos physics
- Supernova neutrinos
- Geo neutrinos
- Low energy dark matter search

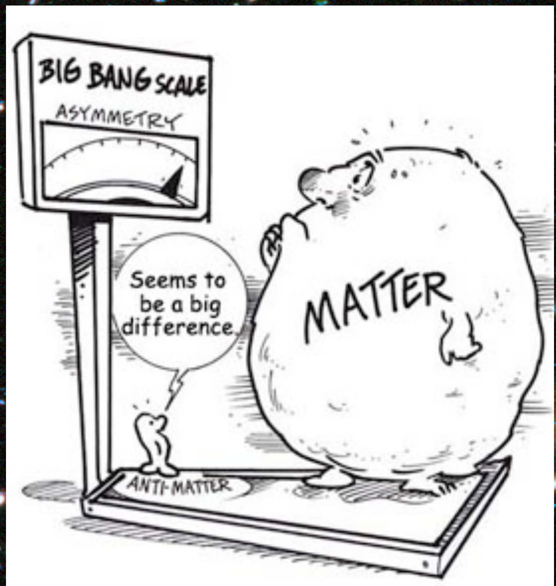
} neutrinos from nature (HKK)

HKK can serve as a neutrino telescope for 20~30 years.

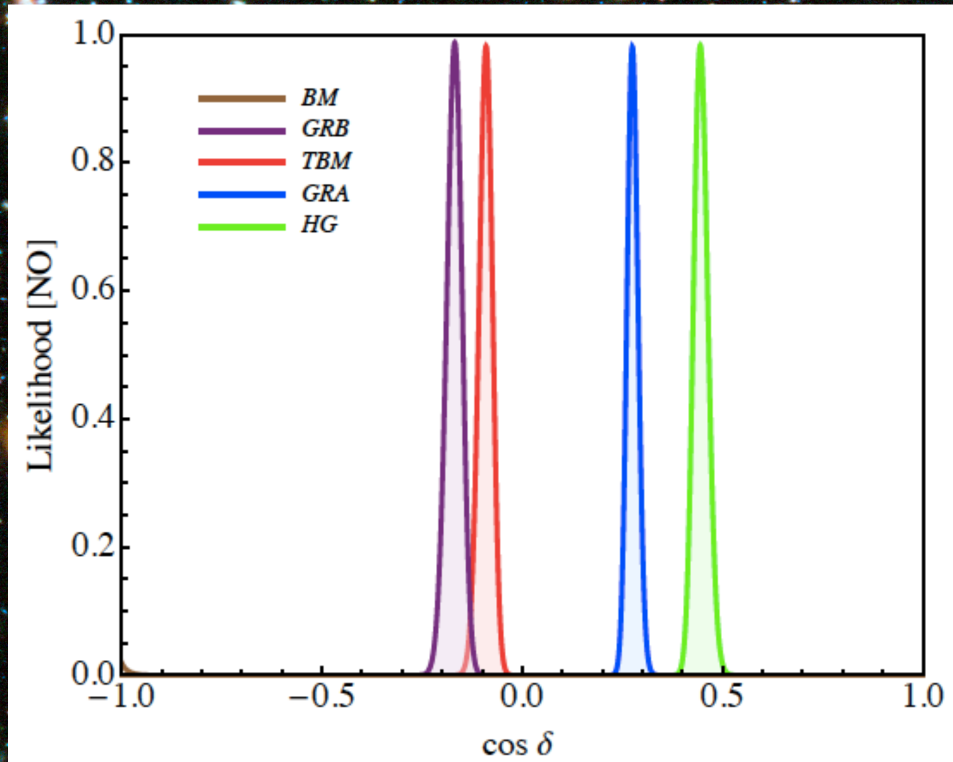
CP violation in leptonic sector

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)?$$

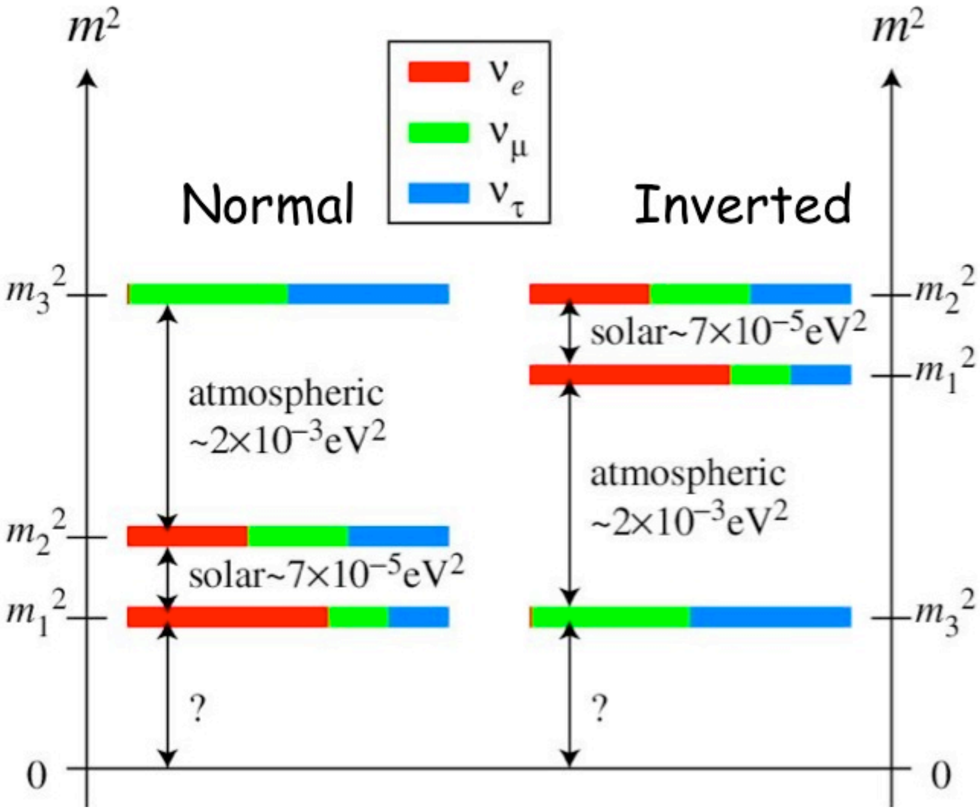
- Matter anti-matter asymmetry



- flavor symmetry



Neutrino mass ordering



- GUT
- origin of the universe
- Connection to Dirac or Majorana nature of ν

δ_{CP} & MO Sensitivity Studies

Simulation parameters

- 2.7×10^{22} POT with $\nu : \bar{\nu}$ = 1 : 3 operation ratio

  → 10 years of operation with 1.3 MW beam

- 187 kton fiducial volume (compared to 22.5 kton for SK)
- Baseline to Korea is 1100 km
- Off-axis beam: 1.3°, 1.5°, 2.0°, 2.5°
- Oscillation parameters: →

$$|\Delta m^2_{32}| = 2.5 \times 10^{-3} \text{ eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m^2_{21} = 7.53 \times 10^{-5} \text{ eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

◆ Note: Relatively simple systematic uncertainty model is used.
More realistic systematic uncertainty implementation is needed.

ν_e appearance probability: address 3 key parameters

If Normal Ordering,
(-) sign is for ν
(+) sign is for $\bar{\nu}$

Mass ordering

θ_{23} and octant

CP

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx 4s_{23}^2 s_{13}^2 \frac{1}{(1\mp r_A)^2} \sin^2 \frac{(1\mp r_A)\Delta_{31}L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21}L}{2E}\right) \sin \frac{(1\mp r_A)\Delta_{31}L}{4E} \cos(\pm\delta - \frac{\Delta_{31}L}{4E})$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}L}{4E}\right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1\mp r_A)^2} \sin^2 \frac{(1\mp r_A)\Delta_{31}L}{4E}$$

solar term: suppressed by Δ^2_{21}

suppressed by $\sin^4\theta_{13}$

ν_e appearance probability (mass ordering)

If Normal Ordering,
(-) sign is for ν
(+) sign is for $\bar{\nu}$

Mass ordering

$$r_A = 2\sqrt{2}G_F N_e E_\nu / \Delta m^2_{31}$$

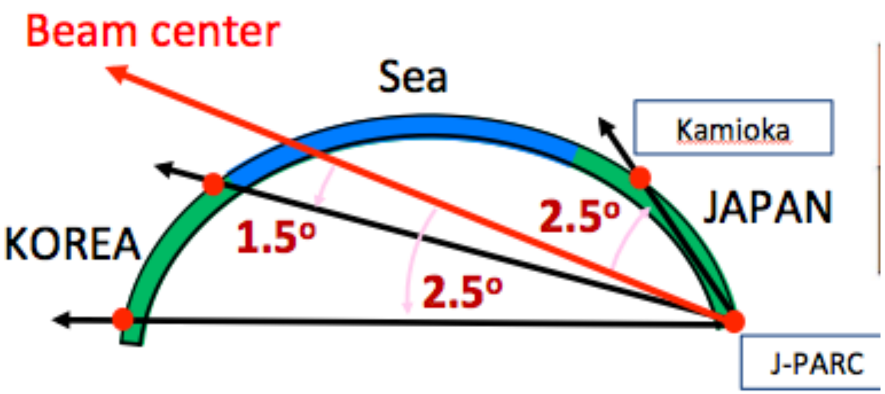
r_A = 6% @0.6GeV
9% @0.9GeV
12% @1.2GeV

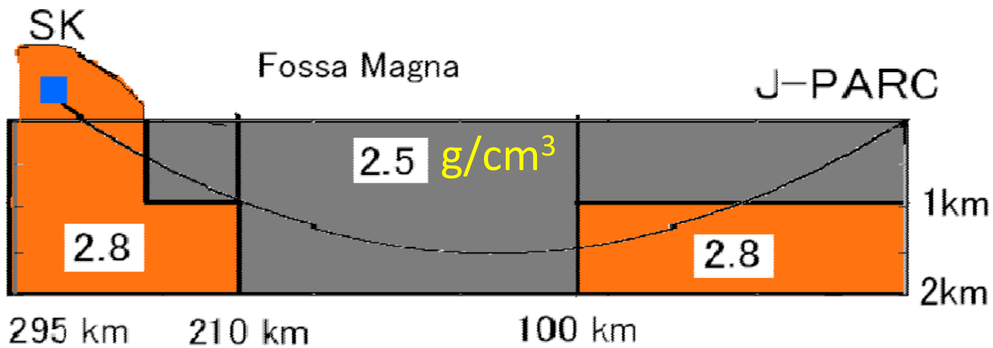
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx 4s^2_{23}s^2_{13}\frac{1}{(1\mp r_A)^2}\sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$
$$+\sin 2\theta_{12}\sin 2\theta_{23}s_{13}\left(\frac{\Delta_{21}L}{2E}\right)\sin\frac{(1\mp r_A)\Delta_{31}L}{4E}\cos(\pm\delta - \frac{\Delta_{31}L}{4E})$$
$$+c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{21}L}{4E}\right)^2 - 4s^2_{23}s^4_{13}\frac{1}{(1\mp r_A)^2}\sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$

1) The amplitude of the oscillation is enhanced or suppressed via the $(1 -/+ r_A)^2$ in the denominator, which @ 1.2GeV is a ± 24% effect.

2) the position of the oscillation extremum, this especially apparent in the 1st oscillation minimum, L/E ≈ $4\pi / (\Delta_{31} * (1 -/+ r_A))$
this changes the energy of the first oscillation minimum by ± 10%.

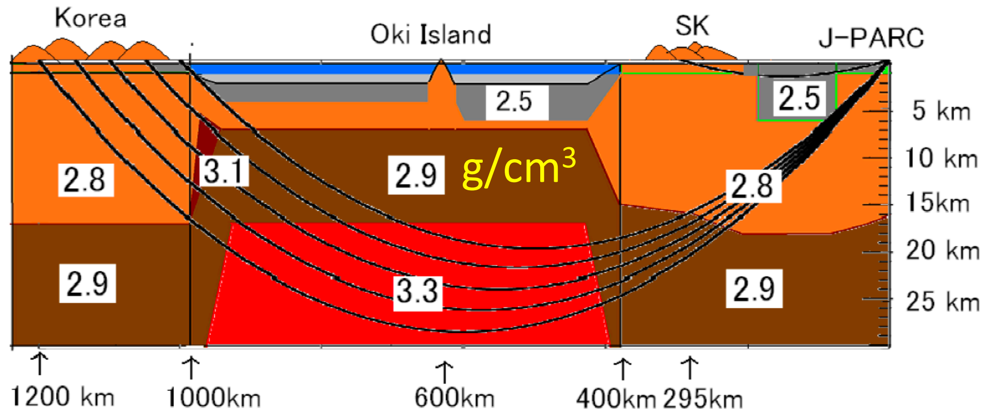
Off-axis Beam and Matter Density





Matter density:

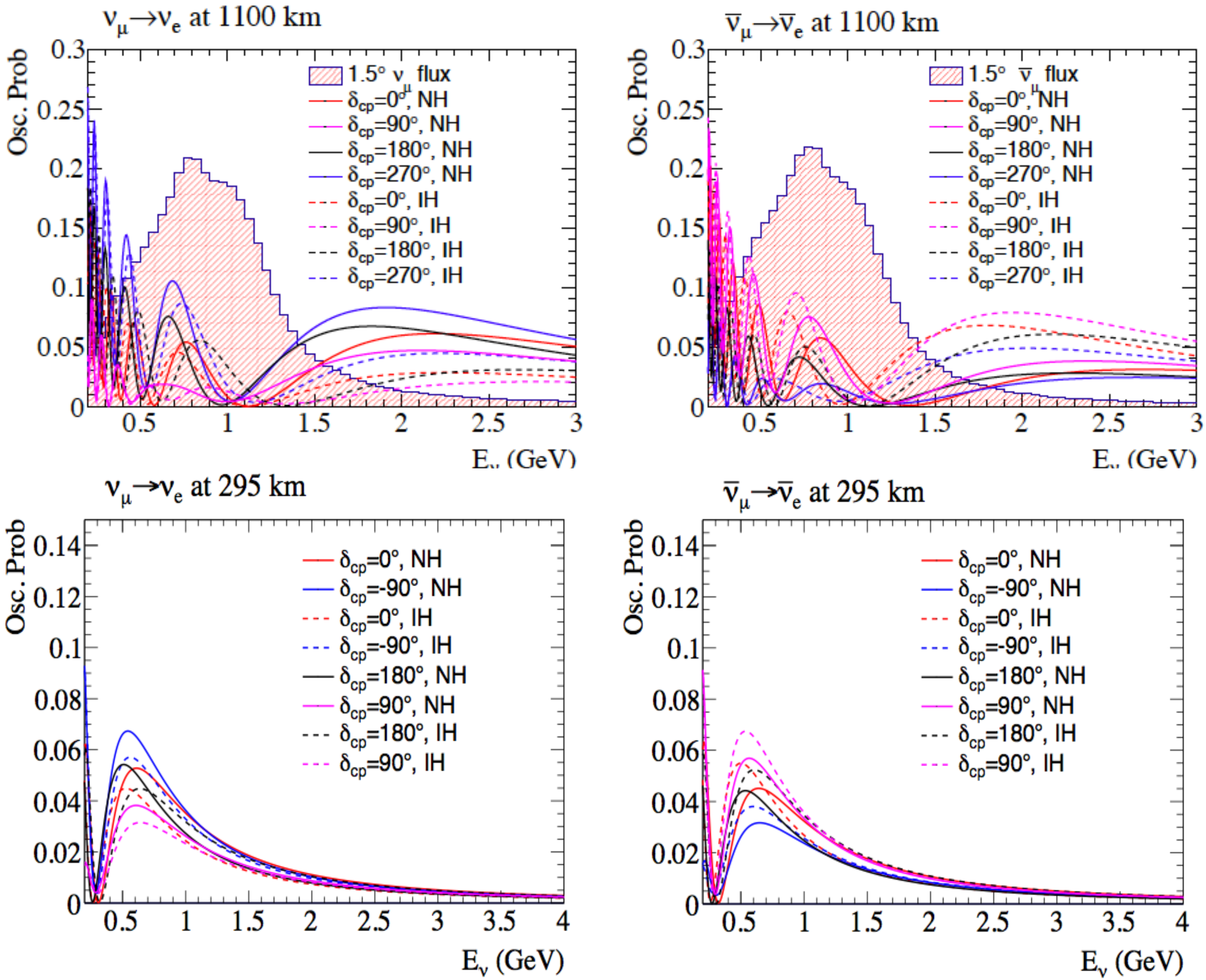
$$r_A = 2\sqrt{2}G_F N_e E_\nu / \Delta m^2_{31}$$



More matter effects

→ better MO determination

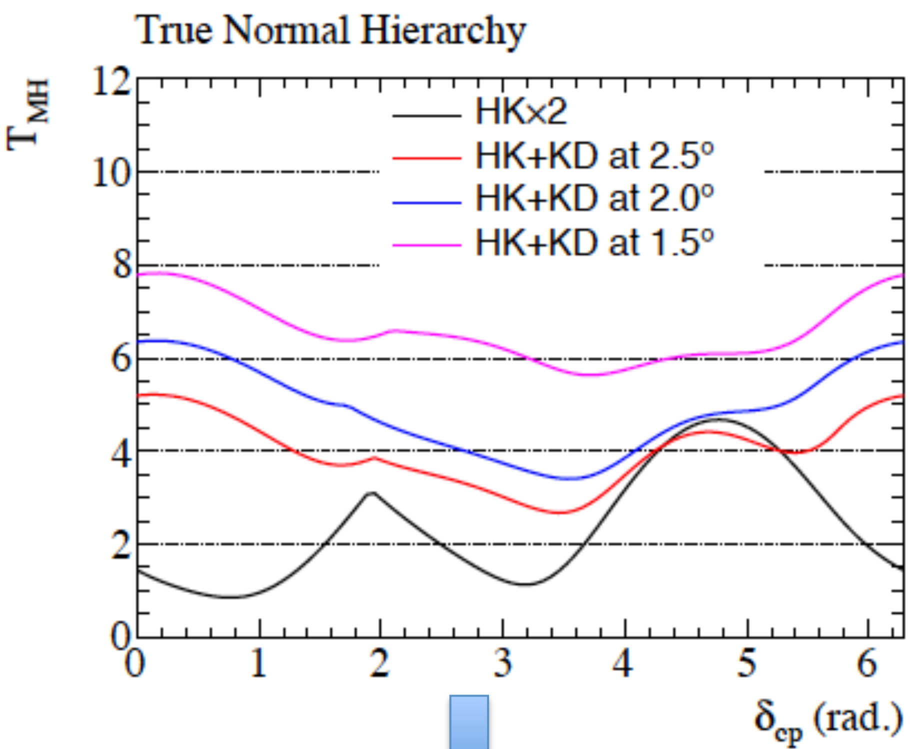
- Longer baseline
- Higher matter density
- Higher neutrino energy

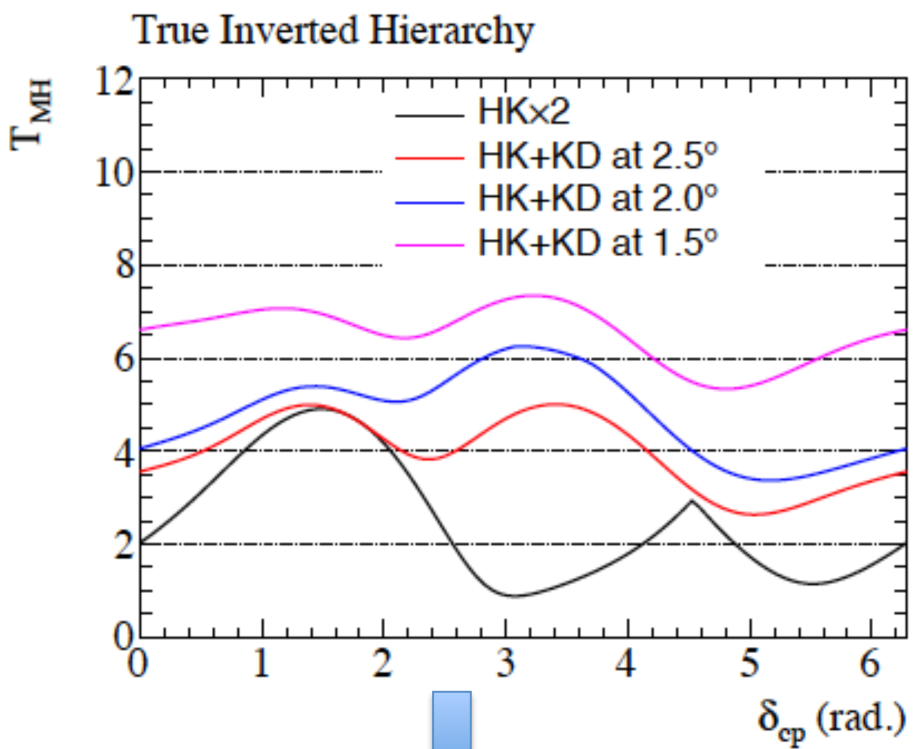


$\nu_\mu \rightarrow \nu_e$ at 1100 km
Osc. Prob
1.5° ν_μ flux
δ_{cp}=0°, NH
δ_{cp}=90°, NH
δ_{cp}=180°, NH
δ_{cp}=270°, NH
δ_{cp}=0°, IH
δ_{cp}=90°, IH
δ_{cp}=180°, IH
δ_{cp}=270°, IH
E_ν (GeV)
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at 1100 km
1.5° $\bar{\nu}_\mu$ flux
$\nu_\mu \rightarrow \nu_e$ at 295 km
δ_{cp}=-90°, NH
δ_{cp}=-90°, IH
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at 295 km

Mass Ordering Sensitivities

Work in progress





HK+KD 1.5°: 6 ~ 8 σ for all δ_{CP}
HK x2 : 1 ~ 4.5 σ for all δ_{CP}
(< 3 σ for most cases)

HK+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}
HK x2 : 1 ~ 5 σ for all δ_{CP}
(< 3 σ for most cases)

ν_e appearance probability: CP violation

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx 4s_{23}^2 s_{13}^2 \frac{1}{(1\mp r_A)^2} \sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21}L}{2E}\right) \sin\frac{(1\mp r_A)\Delta_{31}L}{4E} \cos(\pm\delta - \frac{\Delta_{31}L}{4E})$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}L}{4E}\right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1\mp r_A)^2} \sin^2\frac{(1\mp r_A)\Delta_{31}L}{4E}$$

CP

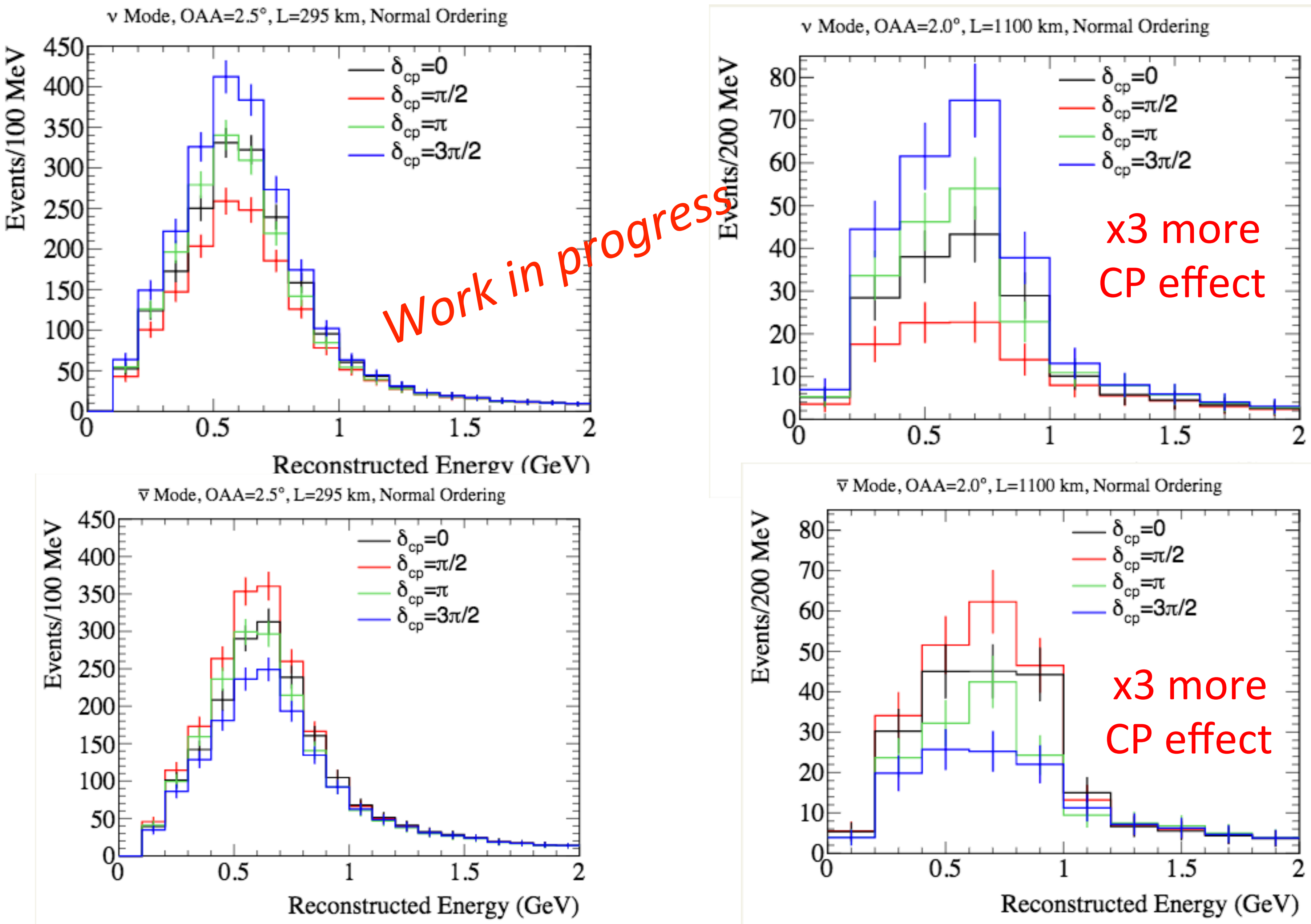
L/E = (π/2)χ(4/Δ_{31}) for 1st max. and (3π/2)χ(4/Δ_{31}) for 2nd max.:

→ x3 more CP effect @ 2nd max

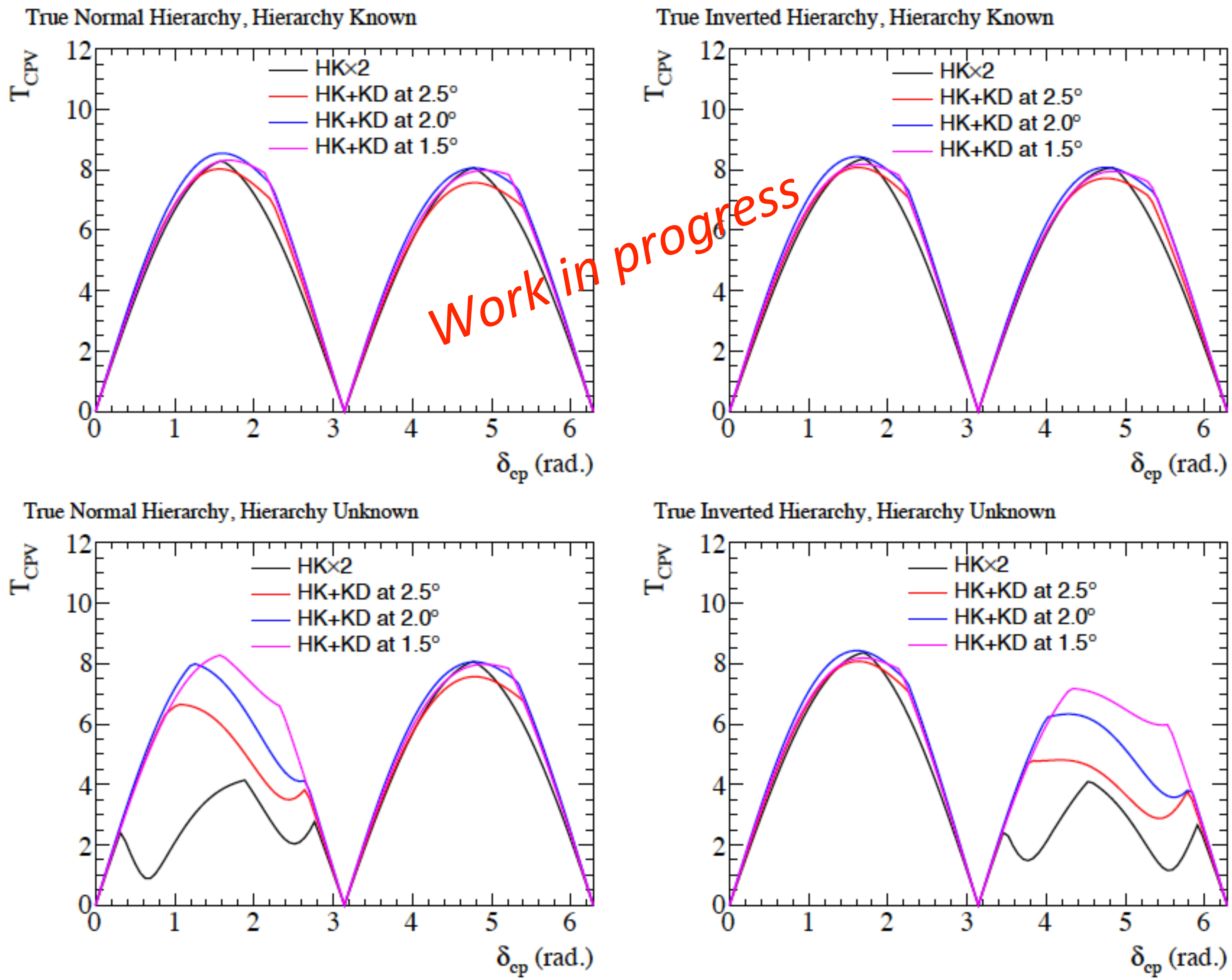
Degeneracies

- sin2θ_{23} → More precise study to be done by T2K/HK
- matter (1+r_A) term causes "discrete" degeneracy with CP: study with E_{rec}>1.2GeV
- degeneracy in phase with Δ_{31} limits CP phase resolution: 2nd max. @T2HKK needed

HK x 1 (295 km) **ν_e candidates** KD (1100 km)

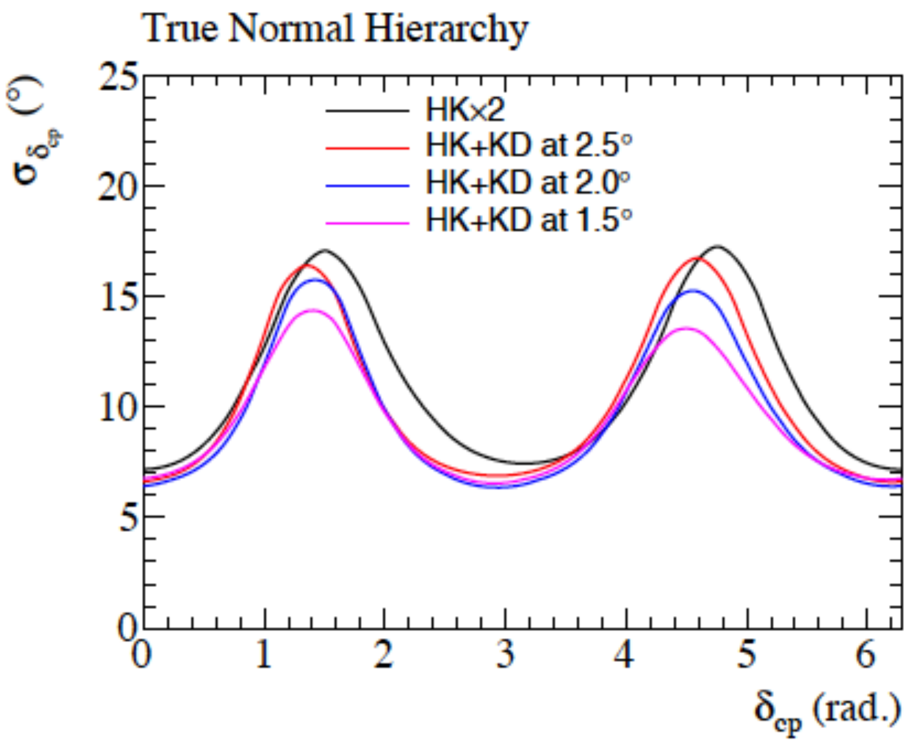


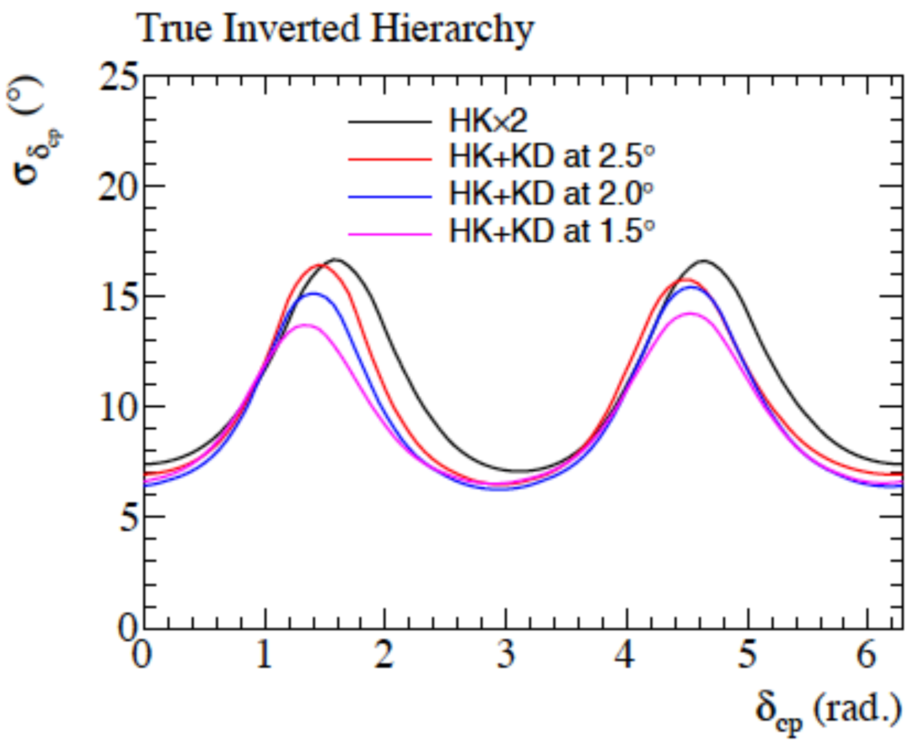
δ_{CP} Sensitivities



δ_{CP} Precision Sensitivities

Work in progress



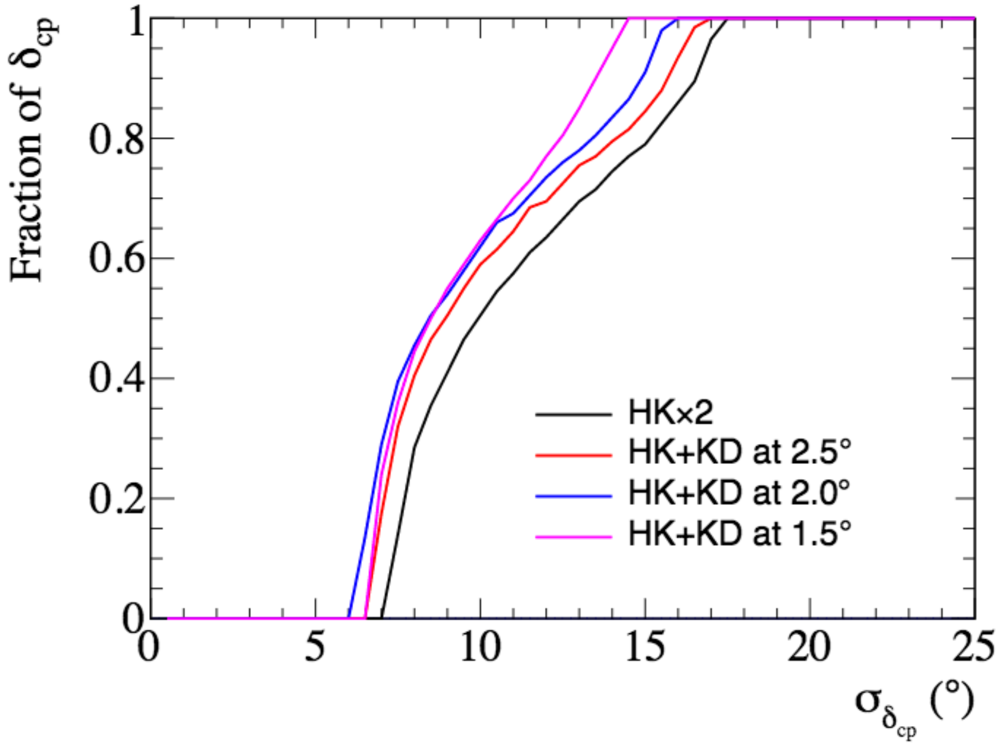


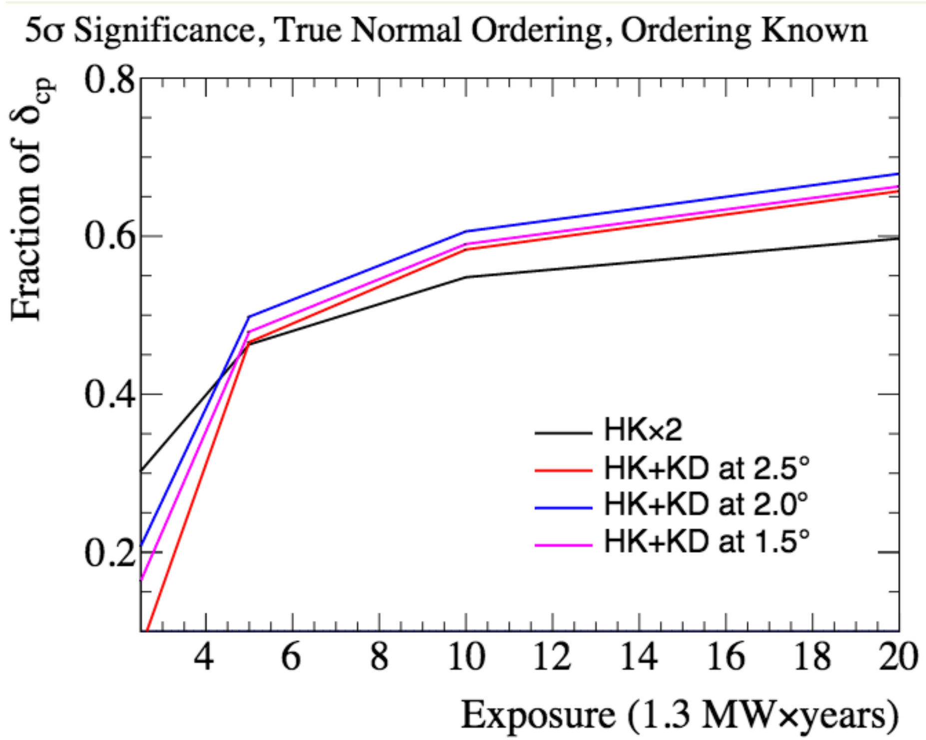
At maximum CP violation: HK+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
HK x2 : $\sigma(\delta_{CP})$ ~ 17 degree

Fraction of δ_{CP}

How much fraction of δ_{CP} can we cover ?

Work in progress





Additional benefits

sources

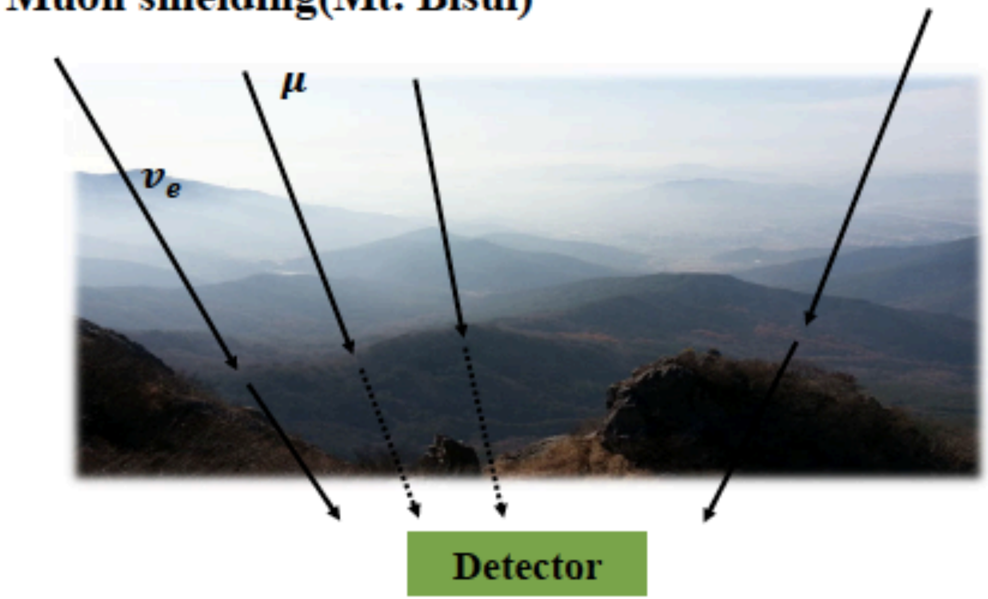
2. Deeper site:
lower muon flux,
lower spallation BKG

3. Geological separation:
signal coincidence,
degeneracy break-up

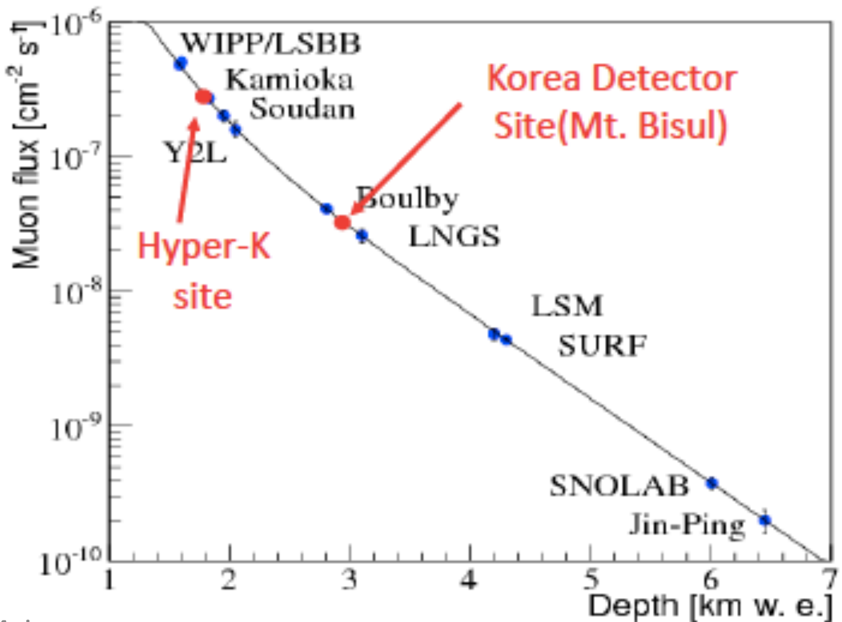
1. Longer baseline:
2^{nd} osc. max,
matter effect

→ δ_{CP}, mass ordering

Muon shielding(Mt. Bisul)



Due to the detector being located deep underground,
The background level is decreased



Muon flux to each laboratory

Additional benefits

❑ Solar neutrino physics

(1) Day/night asymmetry due to MSW matter effect in Earth
(2) HEP solar neutrinos
(3) energy spectrum upturn

} **Sensitivity improves**

❑ Super-Nova Relic neutrino detection

(1) SRN detection capability below 20 MeV improves
(2) Detection efficiency is more than twice in [16, 18] MeV than HK site.

❑ Geo neutrino & Low energy DM

❑ Non-standard new physics

Phys. Rev. D 77, 073007 (2008)

(1) Quantum decoherence,
(2) tiny violation of Lorentz symmetry without/with CPT invariance,
(3) nonstandard neutrino interactions with matter

→ **In most cases, these are improved with T2HKK configuration**

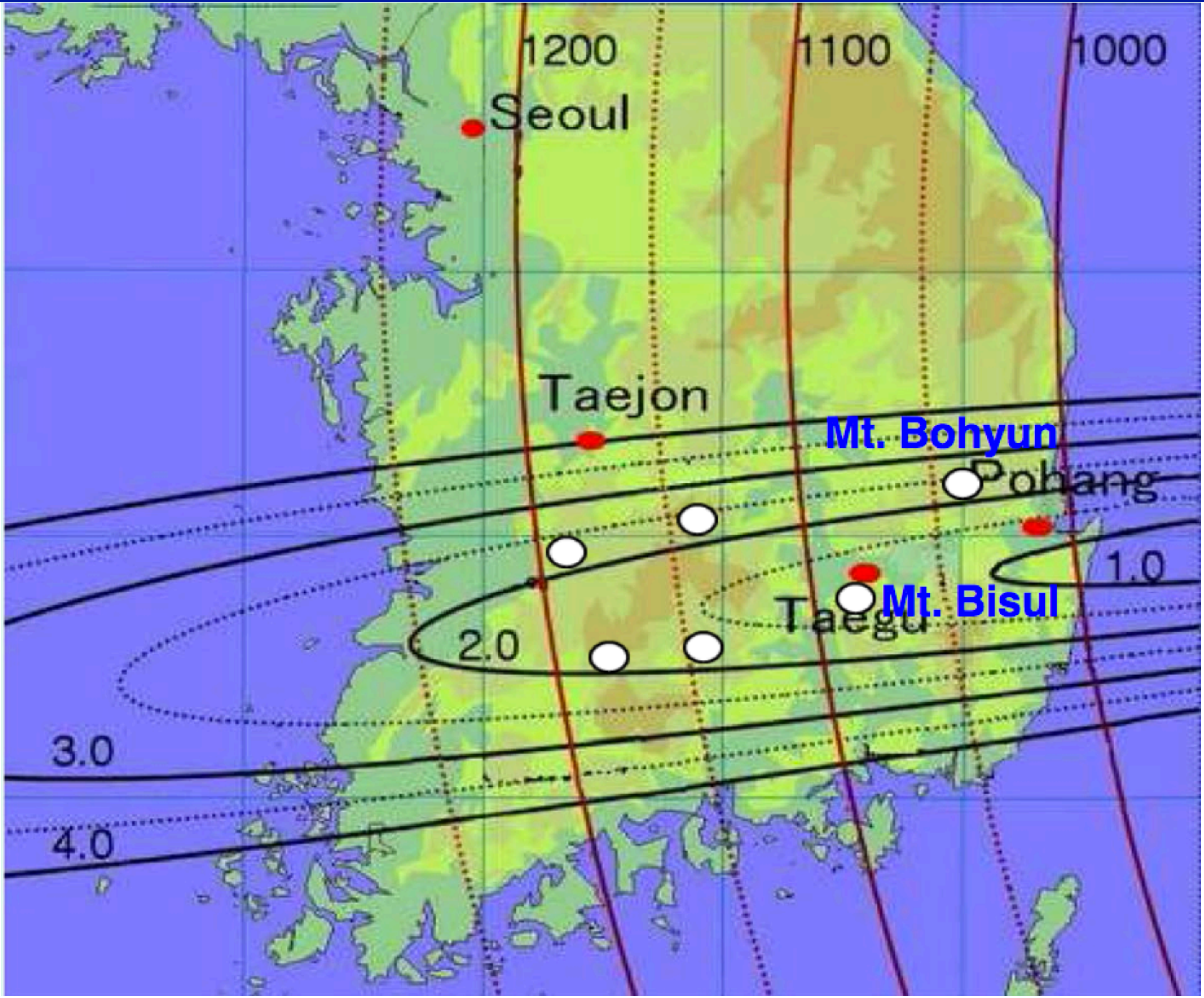
Some candidate sites in Korea

Site candidates for a 2nd osc. maximum detector in Korea

- -- Baselines with 1,000~1,200 km
- -- 2.0~2.5^o or 1.5~2.0^o off axis beam directions
- -- >1,000 m high mountains with hard granite rocks

Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	~1.3^o	1088 km	1084 m
Mt. Hwangmae	~1.8^o	1140 km	1113 m
Mt. Sambong	~1.9^o	1180 km	1186 m
Mt. Bohyun	~2.2^o	1040 km	1126 m
Mt. Minjuii	~2.2^o	1140 km	1242 m
Mt. Unjang	~2.2^o	1190 km	1125 m

Candidate Sites

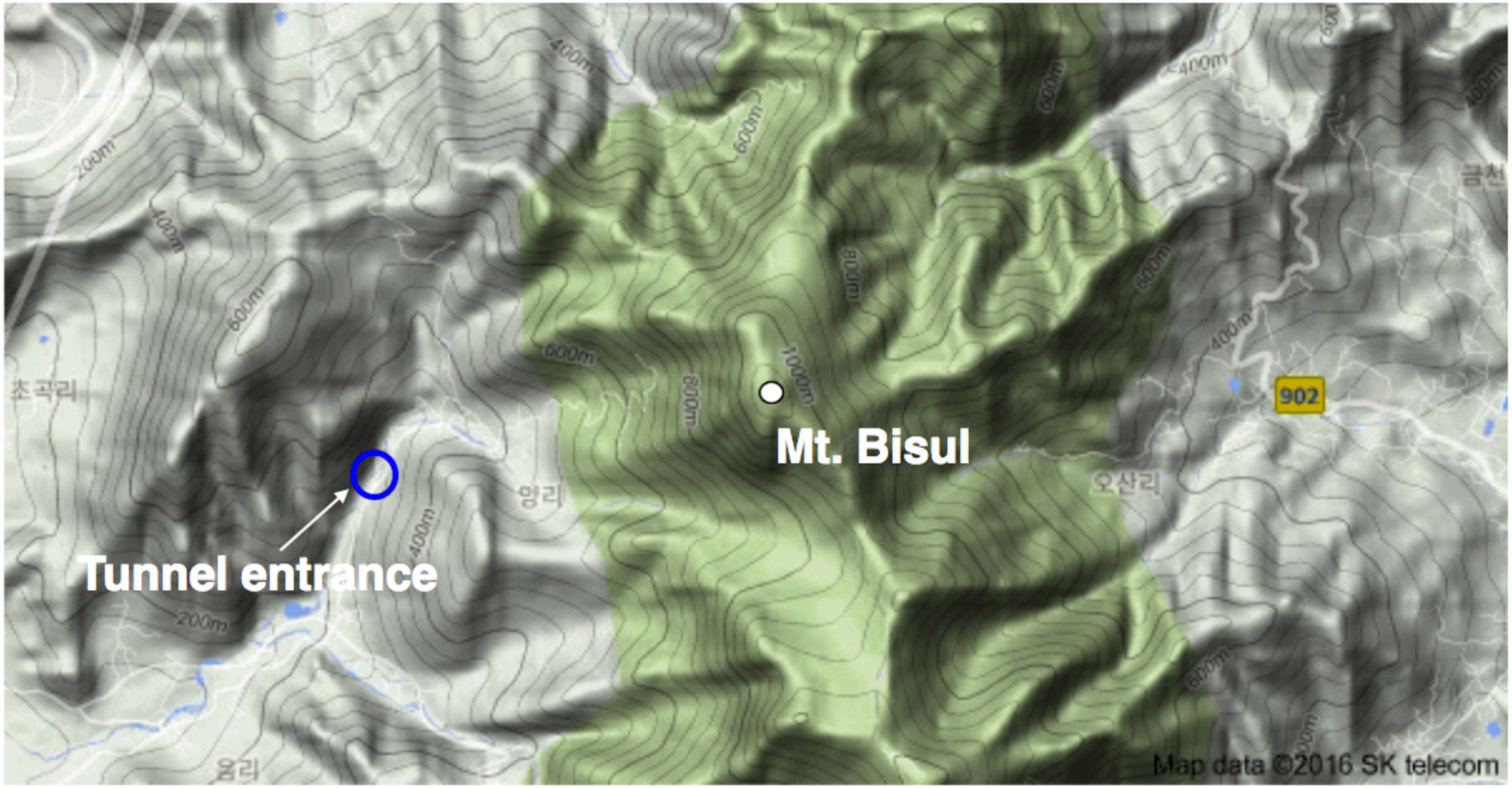


Mt. Bisul

테크노폴리스로
김흥리
김흥2터널
유치곤 터널
4.1km
4.1 km
Mt. Bisul
Technopolis Road
Tunnel entrance
비슬산
상봉재
수성골
갈림길
비슬산
군립공원

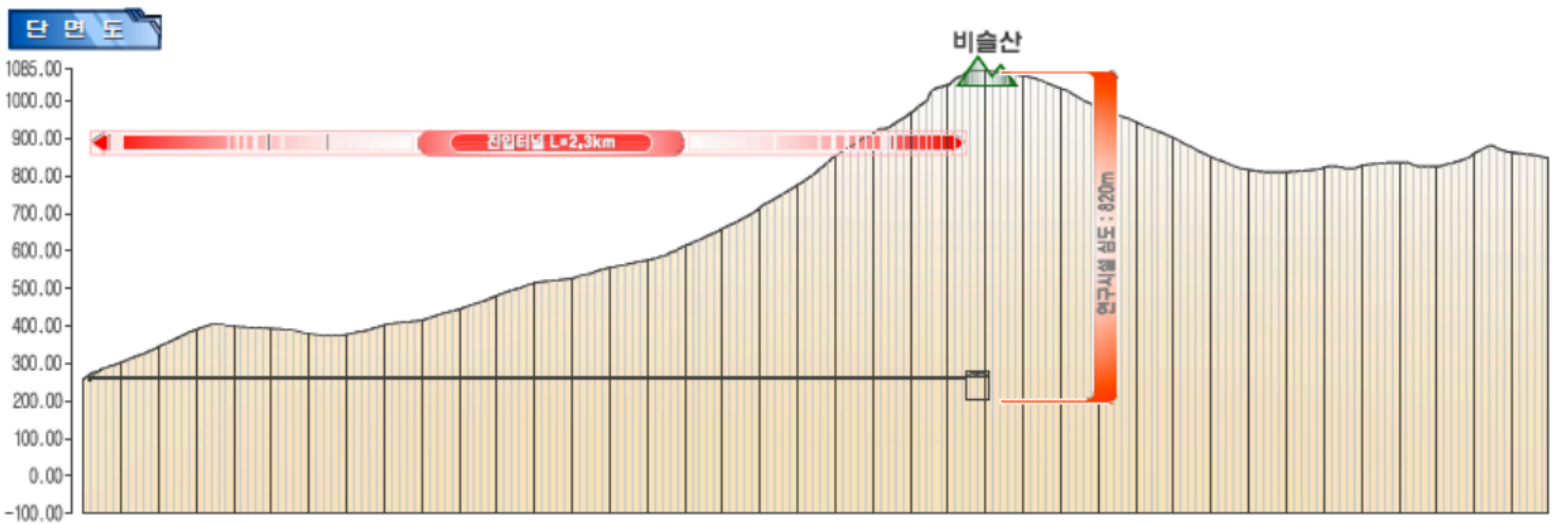
Mt. Bisul (I)

~1,088 km baseline, ~ 1.3° OAB, 1,084 m height



Latitude: N 35° 43′ 00″ longitude: E 128° 31′ 28″

Mt. Bisul (II)



- Overburden: ~820 m (horizontal tunnel)
  ~1000 m (inclined tunnel)

- Access tunnel: ~2.3 km long

- Cost estimate including geological survey will be done

Mt. Bohyun

~1,040 km baseline, ~ 2.2^{o} OAB, 1,126 m height

latitude N 36° 09′ 47″
longitude E 128° 58′ 26″

Brief History of T2HKK (I)

- 2005/2006/2007: a large Cherenkov detector in Korea using J-PARC neutrino beam (T2KK) by T. Kajita.
→ 3 joint workshops supported by KOSEF and JSPS.

- 2015: staged construction of two HK detectors at Kamioka
  2 X 250 kton

- June 1, 2016: offline meeting to begin discussions
  (Canada/Japan/Korea/USA)

- June 2016: a working group effort for sensitivity study

Brief History of T2HKK (II)

- July 10, 2016: official kick-off meeting in London
  → T2HKK proposal accepted in Hyper-K
- Sept. 2, 2016: 1st Korean T2HKK workshop at SNU
- Oct. 20, 2016: KPS pioneer symposium on T2HKK
- Nov, 2016: T2HKK white paper release to arXiv
- Nov. 21-22 2016: 1st International T2HKK workshop at SNU

T2HKK Inauguration
London, July 10th 2016

Announcement of The 1st T2HKK International Workshop

- <u>When</u> : Nov. 21 - 22
- <u>Where</u>: Seoul National Univ., Korea

Workshop indico https://indico.snu.ac.kr/indico/event/6/

We invite all of you !

"Anyone" is very welcome to join this workshop !

Summary & Conclusion

- **Robust and sensitive mass ordering study with T2HKK**
- **CP violation study with less impact from systematics with T2HKK**
  - Important for the discovery of CP violation
  - Resolving degeneracies, e.g. for δcp precision
  - Redundancy: good for exploring new physics effects
- **Does it help for θ_{23} Octant?**
  - Solving degeneracy with matter effect may help.
- **There are additional benefits in low energy physics.**
- **T2HKK's impact would be much more if it starts earlier**
  - **The neutrino beam is already coming to Korea!**

➢ **World class discoveries are expected.**

T2HKK can serve as a neutrino telescope for 20~30 years.